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A Late Glacial ^{10}Be production rate from glacial lake shorelines in Scotland.

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Running Head: A Late Glacial 10Be production rate for Scotland.

ABSTRACT

The identification of tephra within varved deposits of a former ice-dammed lake that existed in Scotland during the Younger Dryas provides an opportunity to calibrate ^{10}Be production rates using previously published ^{10}Be concentrations from the lake shoreline and independently derived ages for the tephra's derived from the Greenland Ice Core records. The best-estimate ages of the tephras yield indistinguishable ^{10}Be production rate values for spallation with an average value of 4.26 ± 0.21 atoms g^{-1} a^{-1} using the 'Lm' scaling scheme. These values are in best agreement with the most proximal reference ^{10}Be production rate from Norway.

Keywords: ^{10}Be; Production rate; Scotland; British-Irish Ice Sheet; Glen Roy

INTRODUCTION

Surface exposure dating using *in situ* produced terrestrial cosmogenic nuclides (TCN) has greatly aided our understanding of the timing and rates of Earth processes, particularly the dynamics of ice sheets past and existing (Balco, 2011). Obtaining precise dating constraints on features related to glaciation using TCN is fundamentally controlled by the accuracy and precision of the known rate at which TCN's are produced in rocks exposed at the Earth's surface.

The CRONUS calculator provides an accessible means for workers to calculate ^{10}Be surface exposure ages through an online interface (Balco et al., 2008). Originally ^{10}Be ages were calculated using a globally averaged production rate with uncertainties of 9-12% compiled mainly from sites in the Northern Hemisphere mid-latitudes. Recent studies in the higher latitudes of both hemispheres (Balco et al., 2009; Fenton et al., 2011; Goehring et al., 2012a,b; Kaplan et al., 2011; Putnam et al., 2010; Young et al., 2013) have reported standardized local production rates 5-15% lower than the global production rate. In addition these local production rates result in improved precision (2-5%) and better agreement between different geochronological techniques (Putnam et al., 2010).

Independently constrained local production rates have been published for many of the extant and former Northern Hemisphere ice sheets with the former British and Irish Ice Sheet (BIIS) a notable exception. Ballantyne and Stone (2012) present a local production rate range ($3.95 \pm 0.13 – 4.16 \pm 0.14$ atoms g^{-1} a^{-1}) based on assumed ages of Younger Dryas glaciers in the Scottish Highlands. These mirror the established trend of being lower than the global production rate but lack independent age control making them vulnerable to circular reasoning. This rapid communication presents the first independently constrained local production rate from a site within the limits of the former BIIS.

SITE DESCRIPTION

Glen Roy, in the Scottish Highlands, is the site of former ice-dammed lakes (Figure 1) that produced a series of shorelines, the 'Parallel Roads of Glen Roy'

(Sissons, 1978). The altitude of the three main shorelines (260, 325, 350 m) was controlled by the height of cols that acted as successive spillways when ice advanced and cut off the previously available drainage route. The resulting sequence of lake level changes is well established (Sissons, 1978) and remains accepted to this day. Recent years have seen a renewal of work in Glen Roy that has produced an annually resolved varve chronology (Palmer et al., 2010) and the first independent age constraints on the 'Parallel Roads' (Fabel et al., 2010)

The varve chronology was constructed from three sites within the former ice dammed lakes (Palmer et al., 2010). The sampled sites are at different altitudes and thus there is an altitudinal control on when lake sedimentation was able to occur. This control, along with the occurrence of common marker horizons and the patterns of changes in mean varve thickness allowed Palmer et al. (2010) to elucidate the durations of the various lake levels. They concluded that the 260 m lake persisted for 192 a before ice advance cut off the associated col and the lake level in Glen Roy rose to 325 m. This lake level lasted for 112 a before further ice advance shut off the 325 m col raising the lake level to 350 m. The 350 m lake level persisted for 116 a before ice retreat led to a re-opening of the 325 m col and a return to the 325 m lake level. This lake level persisted for a maximum of 95 a before final drainage is indicated by the end of varve sedimentation. The 260 m of the falling sequence is not represented in the varve chronology (Palmer et al., 2010).

Fabel et al. (2010) dated the 325 m shoreline to 11.5 ± 1.2 ka (Table 1; n=4, χ^2_R=0.03) using the global production rate (Balco et al., 2008). This shoreline formed during the 112 a of the rising sequence, the 95 a of the falling sequence or, a combination of both. When the lake level was 350 m the sample sites were completely shielded by overlying water. In terms of accumulation of TCN the final abandonment of the 325 m shoreline would best mark the time when ^{10}Be would begin to accumulate. However, to take account of any uncertainties in linking varve properties to changes in lake levels we adopt a more cautious approach and use the median value of the derived calendar age for the entirety of the time when the 325 m lake existed up until final abandonment. This comprises varve years 192-515.

The varve record was originally a floating chronology. The recent identification of tephra (MacLeod et al., 2015) allows for potential correlation to a regional stratotype such as the NGRIP δ^{18}O record (Lowe et al., 2008) and derivation of a calendar age. With an independently constrained calendar age the varve chronology can be used to derive a calendar age for the 325 m shoreline (Table 2) that can be used to calibrate a production rate using the concentrations of samples presented by Fabel et al., (2010).

TOWARDS A LOCAL PRODUCTION RATE

MacLeod et al. (2015) identify two tephras, evidencing two eruptive events, separated by 320 ± 15 varve years. The lower tephra (LMVC-T120), recorded at Loch Laggan East (Figure 1), occurs at varve year 120, while the upper tephra (LMVC-T424), recorded at Glen Turret (Figure 1), occurs between varve years 425-455, the diffuse nature of this tephra peak being attributed to post-depositional varve deformation (MacLeod et al., 2015). Based on geochemical analyses and stratigraphic position the upper tephra was correlated to the Abernethy tephra found in the Abernethy Forest sequence that has been assigned a preliminary age of 11,475 ± 245 cal a BP (2σ range) (MacLeod et al., 2015). However, the occurrence of two tephra layers within the NGRIP ice core record dated to 11,681 ± 106 and 11,926 ± 106 a. b2k provide alternative potential correlations for the upper tephra (MacLeod et al., 2015; Mortensen et al., 2005). The lower tephra is tentatively correlated with the well-documented Vedde Ash (12, 171 ±114 a b2k; (Rasmussen et al., 2006). These varying correlations provide a range of options for placing calendar age constraints on the varve chronology and consequently the sequence of events in Glen Roy (Tables 2 and 3). MacLeod et al. (2015) suggest an age of 11.48 ± 0.25 cal ka BP for the upper tephra making it ~700 a younger than the Vedde Ash. The relative age difference between the upper and lower tephras is 320 ± 20 a suggesting correlation with the 11.93 ka tephra is more likely (Mortensen et al., 2005). Considering this, correlating the lower tephra to the Vedde Ash and the upper tephra to the 11.93 ka tephra is considered the best-estimate, although it is noted a scenario where one or other tephra does not have an equivalent within the NGRIP record is possible but this possibility cannot be assessed. As a result we present production calibrations for all realistic correlations with emphasis on the best-estimate scenario outlined above.

RESULTS AND DISCUSSION

The CRONUS calculator provides a means to calculate a reference LPR using a χ^2 minimization to select the best-fitting ^{10}Be production rate that minimizes the misfit between the measured ^{10}Be concentration and the calculated ^{10}Be concentration based on independent age control (Balco et al., 2008, 2009). Because muonogenic ^{10}Be production is calculated independently within the CRONUS calculator (Balco et al., 2008) following Heisinger et al. (2002a, b) the rates presented and discussed below are for spallation only. The resulting reference ^{10}Be production rates, scaled to sea-level and high-latitude (SLHL), from each of the commonly used scaling schemes are presented in Table 1. The SLHL production rates are 4.24 ± 0.21 - 4.41 ± 0.25 atoms g^{-1} a^{-1} using the Lm scaling scheme and 4.71 ± 0.24 – 4.90 ± 0.28 atoms g^{-1} a^{-1}

using the Li scaling scheme. Further discussion is limited to the Lm Scaling scheme.

^{10}Be production rates were calibrated using four possible tephra correlations (Tables 2 and 3); three scenarios for the upper tephra, one scenario for the lower tephra. Regardless of which correlation is chosen all of the derived local production rates agree within uncertainties. The major factor hindering selection of a single local production rate results from uncertainty in the correlation of the undated tephras in Glen Roy. Despite this limitation the relative age difference between the tephra favours the correlations outlined above allowing derivation of a best-estimate production rate (Table 3). These correlations (upper tephra = 11.93 ka NGRIP tephra; lower tephra = Vedde Ash) yield indistinguishable SLHL production rates of 4.24 ± 0.21 and 4.27 ± 0.22 atoms g^{-1} a^{-1} respectively, giving an average value of 4.26 ± 0.21 atoms g^{-1} a^{-1}. These values do not include a correction for isostatic uplift which is limited to c.10 m since the Younger Dryas (Firth et al., 1993) and thus would make <1% difference to the calculated production rates. The best estimate production rate of 4.26 ± 0.21 atoms g^{-1} a^{-1} is 2.5% lower than the global production rate. When uncertainties are fully considered the datasets are in agreement, most likely as a result of scatter within and between calibration sites used in the global dataset (Goehring et al., 2012a).

Although the Glen Roy production rate agrees within uncertainties with other independent local production rates from high latitudes it is higher than the majority of recently published production rate calibrations from high latitudes and represents the highest updated production rate. The Glen Roy production rate is, however, in best agreement with a production rate calibrated from sites in western Norway (Goehring et al., 2012a, b) which is the closest site both geographically and latitudinally. As discussed by Goehring et al. (2012a) the difference between the Scottish/Norwegian production rates and the lower locally calibrated production rates such as that from New Zealand (Putnam et al., 2010) may be due to unaccounted for changes in air pressure over the late glacial period, which are not an issue for the New Zealand site that is early Holocene in age. The Glen Roy production rate also agrees within uncertainties to the range of local production rates presented by Ballantyne and Stone (2011) with the closest match being to their LPR11.6 (4.16 ± 0.14 atoms g^{-1} a^{-1}). The overall similarities mean the consequences of recalculating ages using the Glen Roy production rate are the same as have been discussed previously elsewhere (Ballantyne and Stone, 2011; Ballantyne, 2012).

CONCLUSIONS

The Glen Roy production rate follows the established pattern of being lower than the global production rate (Balco et al., 2008), however in this case it is only by 2.5% and within uncertainties the production rates are the same. The Glen Roy production rate is in best agreement with the most proximal locally calibrated production rate from western Norway (Goehring et al., 2012a,b). This highlights the potential for production rates to vary both spatially and temporally. The extent of this variation remains poorly constrained and improving our understanding of it is essential to maximize the potential resolution of TCN surface exposure dating.

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FIGURE CAPTIONS

Figure 1. Location map of Glen Roy showing configuration of ice when the Glen Roy lake was at 325 m level corresponding to the sampled shoreline (dots). Spillways shown with arrows. Inset A shows the Younger Dryas ice limits in mainland Scotland.

Figure 2. The Lochaber Master Varve Chronology (Palmer et al., 2010) showing the stratigraphic positions of tephra described in MacLeod et al., (2015). The sand-bed is a stratigraphic tie-point between the various sites used to construct the varve chronology. The sequence and duration of lake level changes is based on Palmer et al., (2010). The onset of varve deposition at Glen Turret at varve year 192 marks the rise in lake level to 325 m as the 260 m lake was too shallow for varves to form prior to this. A distinct increase in varve thickness at varve year 304 is interpreted as representing the rise 350 m. A return to thinner varves at varve year 420 is inferred as indicating the return to 325 m.

Sample	Elevation (m)	Latitude (°N)	Longtitude (°W)	Shielding Factor	Density	Thickness (cm)	$^{10}Be/^{9}Be$ (x 10^{-15})[a]	^{10}Be Concentration
GR0602	325	56.98	4.68	0.9811	2.7	3	96.9 ± 3.55	77978 ± 3610
GR0603	325	56.99	4.68	0.9269	2.7	3	95.1 ± 3.38	72368 ± 3305
GR0604	325	56.99	4.68	0.9543	2.7	3	95.1 ± 3.33	75509 ± 3402
GR0605	325	56.99	4.68	0.6841[b]	2.7	5	63.1 ± 5.58	53588 ± 5237

[a] Relative to NIST SRM 4325 with $^{10}Be/^{9}Be$ taken as 3.06 x 10^{-11}. Blank correction < 3% for all samples

[b] Includes correction for cover by 50 cm of wet peat (density 1.12 g cm^{-3})

Table 1. Sample information and AMS data for original samples from 325 m shoreline from Fabel et al. (2010).

Sequence of events	Varve year	Calendar min age[a]	Calendar max age[a]	325m Shoreline existence
[a] Assumes age of 11,475±245 for the upper tephra at varve year 440±15				
260m lake forms	1	12174	11654	
325m lake forms	192	**11983**	11463	
350m lake forms	304	11871	11351	11562±422
325m lake reforms	420	11755	11235	
End of varve sedimentation	515	11660	**11140**	
[a] Assumes age of 11,681±106 for the upper tephra at varve year 440±15				
260m lake forms	1	12226	12014	
325m lake forms	192	**12035**	11823	
350m lake forms	304	11924	11712	11768±267
325m lake reforms	420	11808	11596	
End of varve sedimentation	515	11713	**11501**	
[a] Assumes age of 11,926±106 for the upper tephra at varve year 440±15				
260m lake forms	1	12471	12259	
325m lake forms	192	**12280**	12068	
350m lake forms	304	12169	11957	12013±267
325m lake reforms	420	12053	11841	
End of varve sedimentation	515	11958	**11746**	
[a] Assumes age of 12,171±114 for the lower tephra at varve year 120				
260m lake forms	1	12404	12176	
325m lake forms	192	**12213**	11985	
350m lake forms	304	12102	11874	11938±275
325m lake reforms	420	11986	11758	
End of varve sedimentation	515	11891	**11663**	

Table 2. Age models for all four potential tephra correlations used to derive reference ^{10}Be production rates. Calendar ages include all counting errors and uncertainties in tephra age.

Glen Roy tephra	Tephra correlation	Corresponding 325 m shoreline age[a]	Reference ^{10}Be production rate [spallation] (			
			St Scaling	Lm Scaling	Du Scaling	De Sca
Upper tephra (LMVC-T424)	Abernethy Tephra (11475 ± 245 cal. a. BP.)	11,561 ± 422 cal. a. BP.	4.42 ± 0.25	4.41 ± 0.25	4.63 ± 0.26	4.60 0.26
	11.68 ka tephra (11,681 ± 106 b2k)	11,768 ± 267 b2k	4.33 ± 0.22	4.33 ± 0.21	4.54 ± 0.23	4.52 0.23
	11.93 ka tephra (11,926 ± 106 b2k)	**12,013 ± 267 b2k**	4.24 ± 0.21	**4.24 ± 0.21**	4.45 ± 0.23	4.42 0.22
Lower tephra (LMVC-T120)	**Vedde Ash (12,171 ± 114 b2k)**	**11,938 ± 275 b2k**	4.27 ± 0.22	**4.27 ± 0.22**	4.48 ± 0.23	4.46 0.23

[a] Based on a total time for formation of 323 ± 8 a. Includes max counting error from NGRIP.

[b] Calculated using the CRONUS online calculator available at http://hess.ess.washington.edu/math/al_be_v22/al_be_calibrate_v22.php

Table 3. Potential tephra correlations, corresponding age of 325 m shoreline and resulting SLHL reference production rates for all the commonly used scaling schemes. (St: Lal, 1991/Stone, 2000; Lm: Lal 1991/Stone, 2000/Nishiizumi et al., 1989; Du: Dunai, 2001; De: Desilets et al., 2006; Li: Lifton et al., 2008). The favoured tephra correlations are in bold.

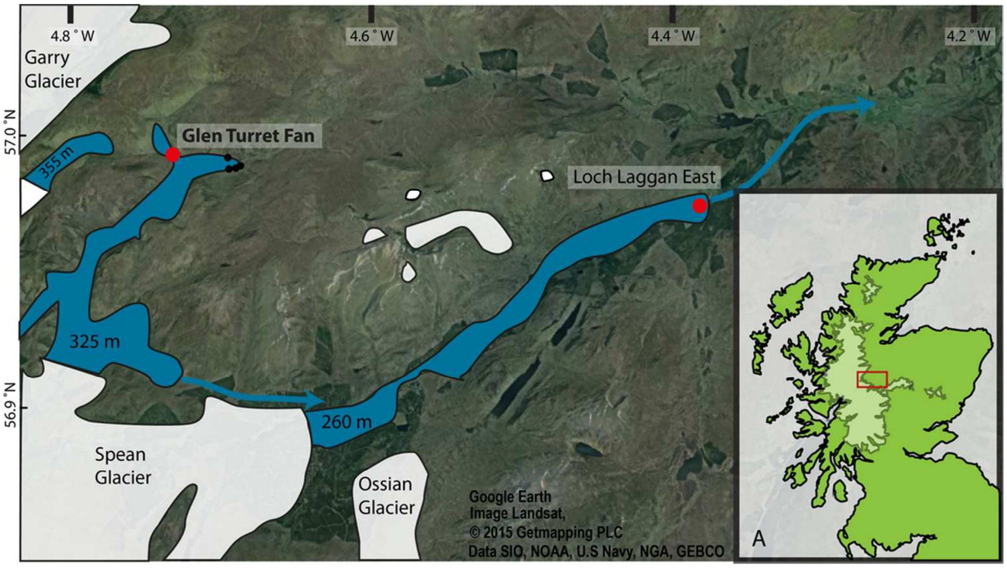

Figure 1. Location map of Glen Roy showing configuration of ice when the Glen Roy lake was at 325 m level corresponding to the sampled shoreline (dots). Spillways shown with arrows. Inset A shows the Younger Dryas ice limits in mainland Scotland.
98x55mm (300 x 300 DPI)

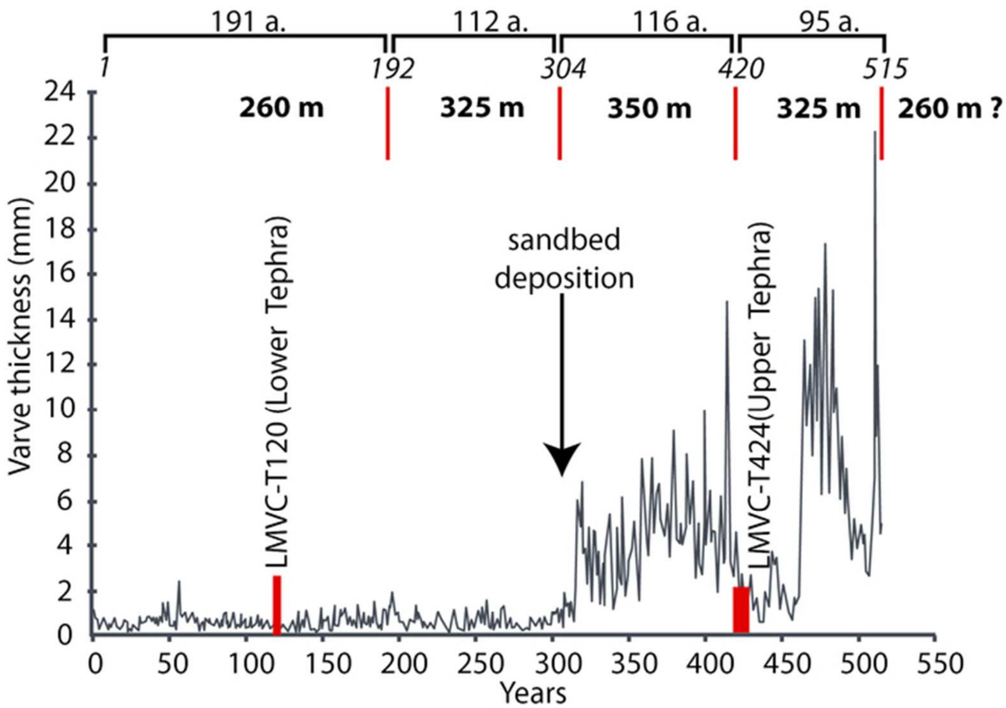

Figure 2. The Lochaber Master Varve Chronology (Palmer et al., 2010) showing the stratigraphic positions of tephra described in MacLeod et al., (2015). The sand-bed is a stratigraphic tie-point between the various sites used to construct the varve chronology. The sequence and duration of lake level changes is based on Palmer et al., (2010). The onset of varve deposition at Glen Turret at varve year 192 marks the rise in lake level to 325 m as the 260 m lake was too shallow for varves to form prior to this. A distinct increase in varve thickness at varve year 304 is interpreted as representing the rise 350 m. A return to thinner varves at varve year 420 is inferred as indicating the return to 325 m.
60x42mm (300 x 300 DPI)